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MEMORANDUM REPORT NO. 1855

PROOF TESTING AND COMPUTER ANALYSIS OF BRL 81/26-MM LIGHT-GAS GUN

by

Vural Oskay

July 1967

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B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

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Vural Oskay

Exterior Ballistics Laboratory

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A B E R D E E N   P R O V I N G   G R O U N D,   M A R Y L A N D

B A L L I S T I C   R E S E A R C H   L A B O R A T O R I E S

MEMORANDUM REPORT NO. 1855

VOskay/sjw
Aberdeen Proving Ground, Md.
July 1967

PROOF TESTING AND COMPUTER ANALYSIS OF BRL 81/26-MM LIGHT-GAS GUN

ABSTRACT

A computer program and its use to simulate the performance of a light-gas gun is described. This technique is applied to simulate proof tests of the 81/26-mm light-gas gun. The analysis is extended to determine performance characteristics and maximum muzzle velocity attainable with a 29-gram launch weight. Results of computer analyses indicate that a sabot/model combination of that weight could be launched at a velocity above 21,000 feet per second if it could be designed to withstand about 1,000,000-g acceleration loads.

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INTRODUCTION

The 81/26-mm light-gas gun was built to launch models for obtaining interferometric data about high Mach number flows. Since the size of the models that can be used for such a study lies within narrow limits, it is important to know the capability of this launcher and its operating characteristics with a given model size (or launch weight).

Determination of gun performance and capabilities by actual testing is very costly and, therefore, impractical when hypervelocity launchers are involved. Some of the reasons for this impracticability are that: (a) these guns are hard to operate and firing is time consuming, (b) the type of information necessary to determine the details of performance would require the gun to be highly instrumented, thus further slowing the testing, and (c) these guns have very short lives owing to the high gas pressures and velocities involved. Hence, it is more convenient to perform a short series of proof tests for an indication of the gun performance at lower velocities and then simulate this performance with a computer program. When this simulation is completed, the program could further be used to determine the characteristics and the capabilities of the gun under loading conditions not covered during the proof testing. This report is an outgrowth of this process.

In the following pages, first a description of the computer program will be given, then the proof testing of the 81/26-mm light-gas gun will be discussed, and finally the mathematical simulation of these test results and the analysis of the gun performance will be described.

COMPUTER PROGRAM

An interior ballistic program developed by Baer and Smith[1*] was used for the performance analysis of the 81/26-mm light-gas gun. This program utilizes the Richtmyer-Von Neuman "q" method to describe the

[*] *Superscript numbers denote references which may be found on page 29.*

motion of the light gas between the model and the piston. The gas column is divided into 50 mass points having volume, temperature, and pressure characteristics. Assumptions used in the mathematical model are as follows:

1. the light gas behaves as an ideal gas with constant specific heats

2. frictional losses experienced by the piston and the model in the pump and launch tubes, respectively, are functions of piston and model travel

3. frictional losses between the light gas and the gun, including the transition section, are negligible

4. heat loss from the light gas to the gun is negligible

5. conventional interior ballistic equations determine the pressure of the powder gas propelling the piston

The input data to the program include the following:

1. gun design parameters: powder chamber volume, pump tube dimensions, transition section dimensions, launch tube dimensions, and maximum allowable light-gas pressure during the launching cycle

2. gun loading parameters: piston weight and length, light-gas properties (specific heat ratio, initial pressure and temperature, molecular weight), and model weight

3. igniter data: weight, specific heat ratio, force constant, and flame temperature

4. powder data: weight, specific heat ratio, force constant, burning rate constants (α and β), flame temperature, and grain dimensions of the propellant

5. parametric constants: shot-start pressure (defined as the pressure equivalent of the force required to initiate projectile motion) and resistive pressure (defined as the pressure equivalent of the dissipative forces, such as tube friction, encountered during the launch cycle) for both the piston and the model (These constants can also be taken into account if any of the above assumptions prove to be erroneous during the attempt to match the computer results with the actual test data.)

6. duration of the print interval

The output of the computer program is given in both graphical and tabulated form. The plotted curves show (a) piston velocity, breech pressure, and pressure immediately ahead of the piston as functions of piston travel; and (b) model velocity and base pressure as functions of model travel.

Each interval of the printout includes:

1. time elapsed since ignition
2. piston position, velocity, and acceleration
3. piston configuration (position, velocity, area of both the leading and the trailing faces of the piston, and the piston length)
4. breech pressure and piston base pressure
5. model position, velocity, and acceleration
6. pressure immediately ahead of the piston
7. model base pressure
8. maximum light-gas pressure between the piston and the model
9. percentage of propellant burned
10. position, velocity, temperature, pressure, and local Mach number of each of the 50 mass points between the piston and the model

The launch cycle terminates when the model leaves the launch tube; the muzzle velocity of the model and the maximum light-gas pressure encountered during the launch cycle are also displayed in its printout.

COMPUTER SIMULATION OF GUN PERFORMANCE

Performance of a light-gas gun is simulated under the assumptions described in the previous section if the calculated muzzle velocity of the model is matched to the experimentally obtained value for the same loading conditions. These loading conditions and the model velocity are determined by the existing test data; the gun dimensions are fixed by the design of the gun.

With the input data fixed, matching of the calculated and the experimental muzzle velocities could be attained only by varying the values of the parametric constants of the program, i.e., shot-start and resistive pressures for both the piston and the model. Therefore, simulation of the performance of a light-gas gun could be accomplished only after the completion of (a) at least a partial proof testing of the gun to determine its operating characteristics and (b) a computer study to determine the best values of the parametric constants of the program in order to match the test data obtained during the proof tests.

The test set-up and the results of the proof tests of the 81/26-mm light-gas gun are described in the next section. Another section is reserved for the description of the parametric study based on these proof tests.

PROOF TESTS OF 81/26-MM LIGHT-GAS GUN

The 81/26-mm light-gas gun, shown in Figure 1, is a two-stage gun with a powder-chamber volume of 620 cubic inches. The pump tube (3.2-inch inside diameter and 238.8-inch length) holds the piston, and is pressurized to 200 psig with helium. The 1.015-inch inside diameter, 216-inch long launch tube is connected to the pump tube through a long conical transition section 12.9 inches long.

Models used during the proof testing of this gun were 29-gram 1.5-caliber long, Lexan cylinders. Their weight, thus their length, was selected to simulate the expected weight of a model (saboted, 3/4-inch aluminum sphere) to be used in a later test. The model was separated from the pump tube by a Lexan shear disk 1/4 inch thick.

The Test

Proof tests consisted of firing the gun several times with each of three different powder weights and determining average breech pressures and model velocities as functions of powder weight. Breech pressures were measured with one hat-gage and two T-18 copper-crush gages (the

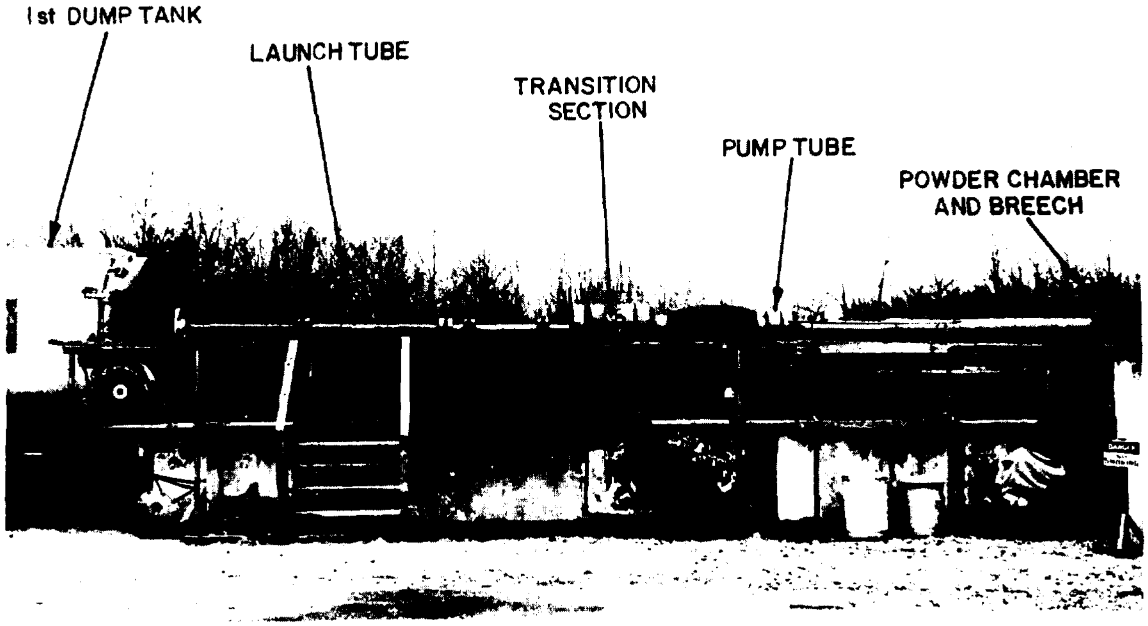

Figure 1. Photograph of the 81/26-mm light-gas gun

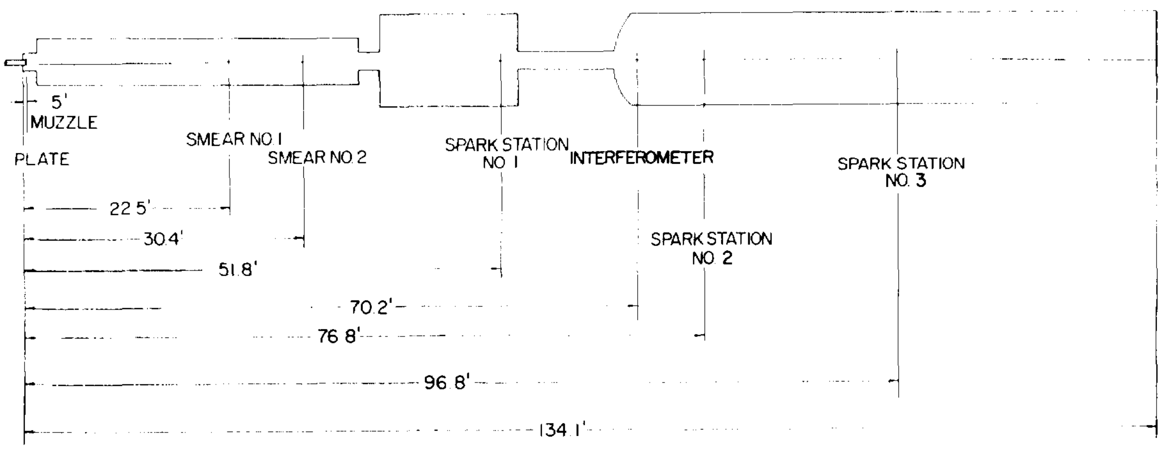

Figure 2. Schematic of the white range

copper-crush gages giving breech pressure values, on the average, about 1000 psi lower than the hat-gage). For the gun simulation computations, the breech pressures obtained with the hat-gage were used.

The White Range[2] instrumentation scheme was used in the determination of the muzzle velocities. This free-flight range, schematically shown in Figure 2, consists of two dump tanks and an instrument tank. The first dump tank is 5 feet in diameter, 32 feet long and contains two smear camera stations. The first camera is 4 feet from the gun muzzle, and it is used only to observe sabot separation. The second smear camera is used for velocity determination. The second dump tank is 10 feet in diameter and 16 feet long. It contains one of three Fresnell-lens shadowgraph stations. The instrument tank is also 10 feet in diameter. It is 64 feet long and contains the remaining two shadowgraph stations and a Mach-Zehnder interferometer.

A complete description of the instrumentation of the White Range is given in Reference 2; only those parts of the instrumentation pertinent to velocity determination will be discussed here.

The first velocity measurement is made by the dual-image Fastex camera station, shown schematically in Figure 3. This smear camera uses a photographic technique developed at the Naval Research Laboratory in Washington, D.C.[3] The camera takes two smear photographs of the model and sabot as they pass in front of the two viewing ports. By use of a mirror system, both images are exposed on a single strip of film, Figure 4, traveling through the camera. Due to the motion of the film, these images are displaced relative to one another. Since the speed of the film can be accurately determined by the timing marks, the time required for the model to travel the distance between the two ports is easily calculated by measuring the displacement between the two images. Hence, a good velocity determination can be made for the model and for the sabot parts.

The shadowgraph stations are used to obtain three additional velocities along the trajectory of the model. Each station, Figure 5, is located by an optical survey to within 0.010 inch. A beaded-wire

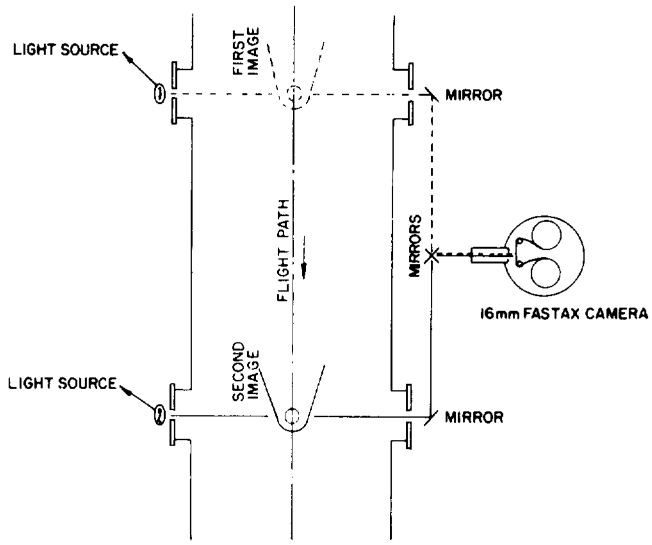

Figure 3. Schematic of dual image Fastax camera station

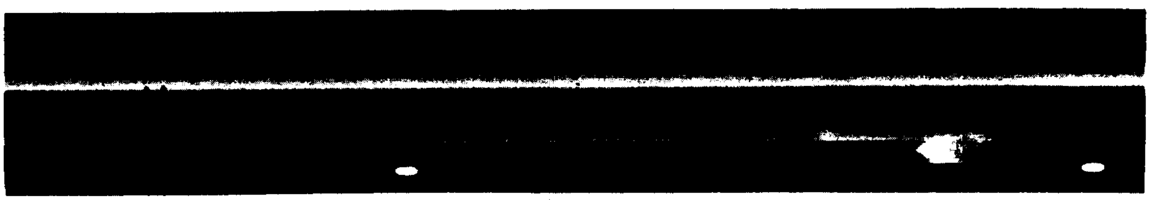

Figure 4. Reproduction of a 16-mm Fastax camera record

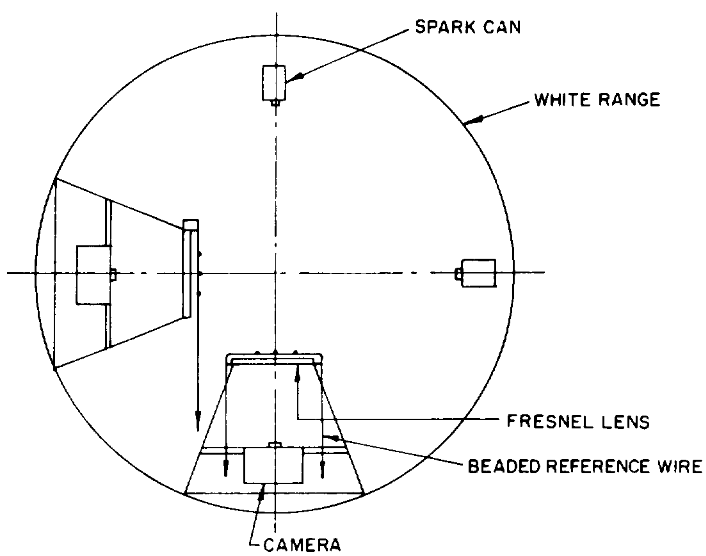

Figure 5. Schematic of a shadowgraph station

reference system is also located by the survey and is used to determine the model's position in space. A 1.6-megacycle Potter counter chronograph is connected to the electrical circuit of each shadowgraph station. These chronographs are started by a signal from the firing circuit of the gun and stopped by the triggering of the spark sources of the corresponding shadowgraph stations. Readings from the counters and the known distances between the stations permit determination of model velocity along its trajectory.

This network of data stations gives average model velocities at the following distances from the gun muzzle:

Location	Distance (ft)
Second smear camera station	26.0
Between shadowgraph stations 1 and 2	64.5
Between shadowgraph stations 1 and 3	74.5
Between shadowgraph stations 2 and 3	86.5

Model velocities thus determined are then extrapolated back to the gun for an estimate of the muzzle velocity. This method is good for determining the velocity of each round; but when used to determine the range of muzzle velocities of tumbling cylinders, for a given loading condition, the result is a larger velocity dispersion than would be encountered with spheres due to drag variations from round-to-round.

The Test Results

For ease of handling, a 3/4-inch aluminum sphere and sabot were simulated with a 29-gram, 1.5-caliber long Lexan cylinder during the proof test. The gun loading conditions were:

Piston weight	10 pounds
Pump-tube gas	Helium at 200 psig
Range pressure	76 mm mercury (absolute)

Also, 2.0, 2.5, and 3.0 pounds of M6-MP (0.0375-inch web) powder were used during the tests.

Test data used to determine the parametric constants of the computer program were (a) average breech pressures measured with the hat-gage, and (b) average muzzle velocities. These data are listed below as functions of powder weight:

Powder weight (lb)	No. of rounds	Average breech pressure (psi)	Average muzzle Velocity (ft/sec)
2.0	3	5170	10,400
2.5	6	6020	11,800
3.0	3	8460	13,400

DETERMINATION OF PARAMETRIC CONSTANTS

Simulation of the gun performance was accomplished by determining values of the parametric constants of the computer program which permitted the best matching of the test results listed in the previous section. A description of this procedure follows.

As stated previously, the input to the program includes gun dimensions, propellant characteristics, light gas properties, gun loading conditions, and values of the four parametric constants. For reference, these input data are summarized below:

1. Gun dimensions

Powder chamber volume	620.0 cubic inches
Pump tube diameter	3.2 inches
Pump tube length	238.4 inches
Transition section length	12.9 inches
Transition section shape	Conical
Launch tube diameter	1.015 inches
Launch tube length	216.0 inches

2. Propellant data

Igniter type	Black powder
Igniter weight	0.131 pound
Powder type	M6-MP, 0.0375-inch web
Powder weight(s)	2.0, 2.5, and 3.0 pounds

3. Nominal gun loading conditions

Piston weight	10 pounds
Piston length	14 inches
Model weight	29 grams
Pump-tube gas	Helium
Initial pump-tube gas temperature	$350^{\circ}K$
Initial pump-tube gas pressure	200 psig

4. Parametric constants

Piston shot-start pressure	2000, 3000, 4000, and 5000 psi with 500 psi for piston resistive pressure
Piston resistive pressure	0, 500, and 1000 psi with 4000 psi for piston shot-start pressure
Model shot-start pressure	2000, 2500, and 3000 psi with 0 psi for model resistive pressure
Model resistive pressure	0, 200, and 400 psi with 2000 psi for model shot-start pressure

The nature of the assumptions made in arriving at the mathematical model of the light-gas gun performance enables a parametric study like this to be divided into two parts:

a. determination of shot-start and resistive pressures for the piston, because its performance is governed by the conventional interior ballistic equations as modified only by the pressure ahead of the piston

b. determination of the model shot-start and resistive pressures to match the existing test data once the values of the parametric constants of the piston were set.

Figures 6, 7, and 8 show results of the effort to determine best values of the piston shot-start and resistive pressures. Since the model parametric constants do not affect the calculated piston performance, they are not indicated on the figures.

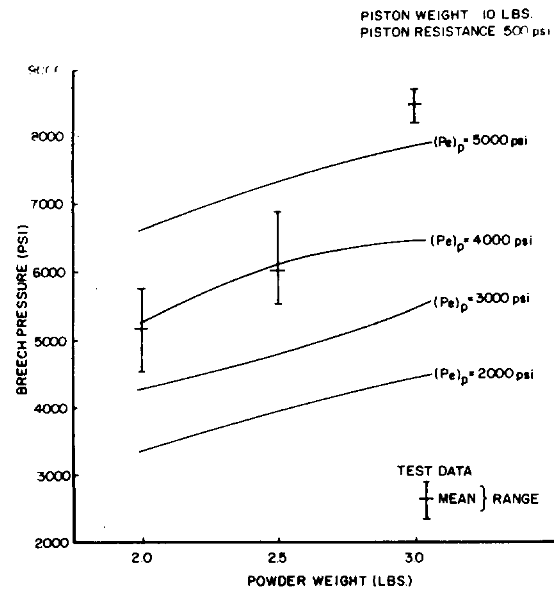

Figure 6. Breech pressure vs powder weight, with piston shot-start as parameter

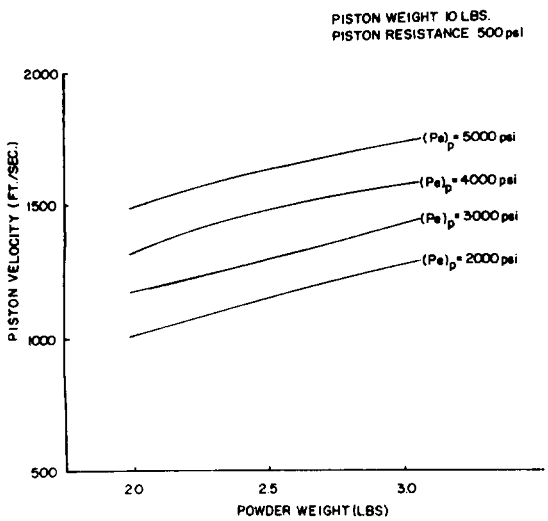

Figure 7. Piston Velocity vs powder weight, with piston shot-start as parameter

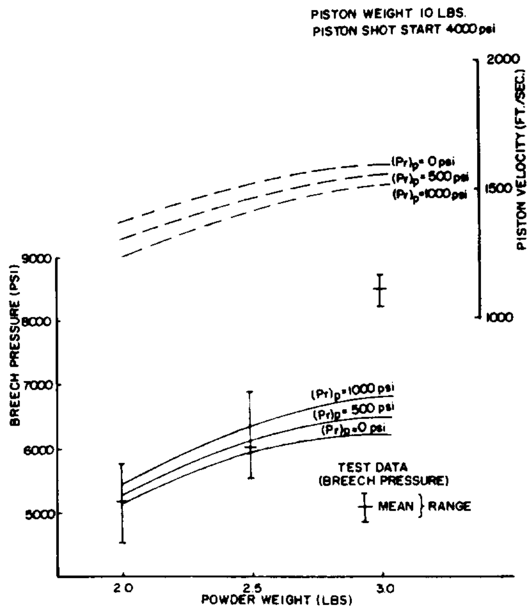

Figure 8. Piston performance vs powder weight, with piston resistance as parameter

Figures 6 and 7 show effects of piston shot-start pressure on the breech pressure and the piston velocity, respectively. These graphs indicate that both the breech pressure and the piston velocity increase with increasing piston shot-start pressure. Test data shown in Figure 6 are the breech pressures measured with hat-gages during the proof tests of the 81/26-mm light-gas gun. From the results indicated in Figure 6, we can conclude that the value of the piston shot-start pressure which best simulates the available data is 4000 psi. The difference shown in Figure 6 between measured and computed breech pressures at 3.0-pound powder weight is thought to be largely due to a chance combination of experimental variables. One of these variables is the diameter of the piston. If, because of machining tolerances, the diameter of the pistons used during the 3.0-pound powder-weight tests were larger than the others, then higher shot-start pressures would result, with consequently higher breech pressures.

Figure 8 shows the effects of piston resistive pressure on the piston performance. Indications are that increased piston resistive pressure increases the breech pressure while decreasing the piston velocity. Test data shown in Figure 8 are again the measurements obtained during the proof testing. According to these measurements, any value of the piston resistive pressure between 0 and 500 psi can simulate the piston performance. For the remainder of this study, 500 psi is used.

After the values parametric constants of the piston were determined, an attempt was made to determine the effect of varying model resistive pressure on the muzzle velocity for an arbitrary shot-start pressure, say 2000 psi. Results of these calculations are shown in Figure 9. Since the ratio of model bearing area to its cross-sectional area is about one-fourth the same ratio for the piston, a model resistive pressure of 200 psi was used as a starting point. 0 and 400 psi were used to obtain additional curves as shown in Figure 9. These curves indicate that for the calculated conditions the model velocity increases with increasing resistive pressure, the reverse of the result obtained for the piston performance. This anomalous result may be an indication that

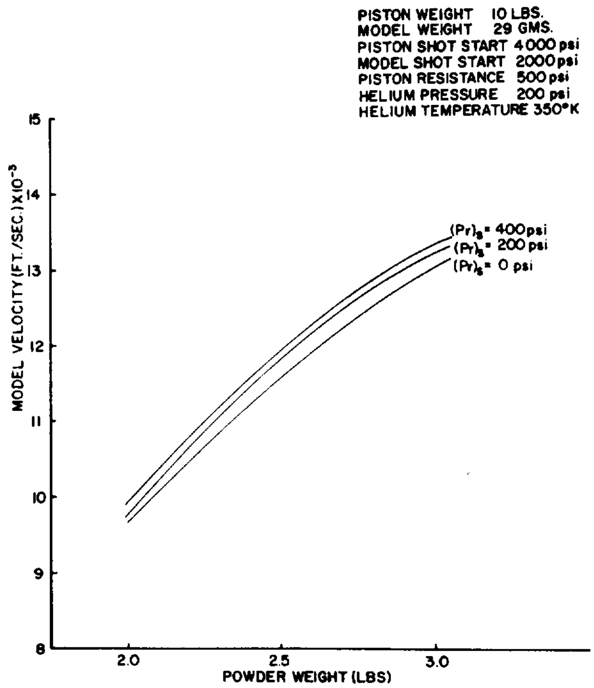

Figure 9. Model velocity vs powder weight, with model resistance as parameter

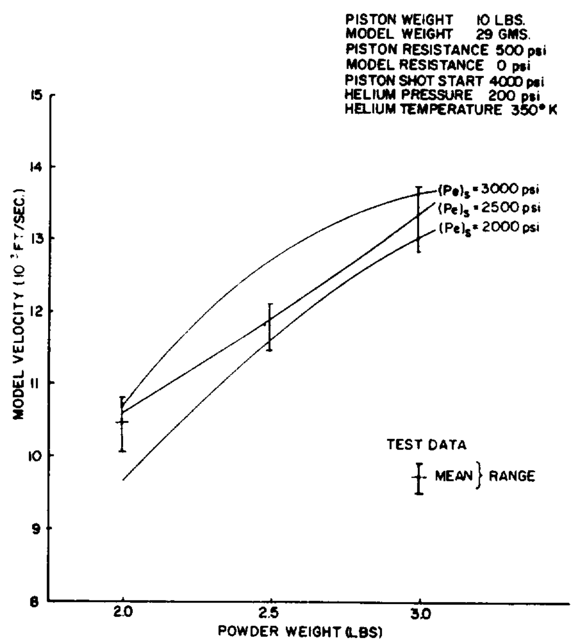

Figure 10. Model velocity vs powder weight, with model shot-start as parameter

the launch tube is not long enough for the friction effects to start dominating the gun performance. Calculations also indicate that the model base pressure is several orders of magnitude larger than any value of model resistive pressure that could reasonably be assumed, thus reducing the effects of the latter even further. Therefore, during the remainder of this study, the value of model resistive pressure is assumed to be 0 psi.

To complete the simulation of the 81/26-mm light-gas gun performance, the value of the model shot-start pressure needed to be determined. Results of this determination are presented in Figure 10. A comparison with the experimentally obtained model velocities, shown in the figure by the scatter bars, indicates that a model shot-start pressure of 2500 psi gives the best simulation of the gun performance under the assumed conditions.

At this point in the study, it was noticed that the value of the initial gas temperature used in the analysis, 350°K, was erroneous. Therefore, calculations to determine the model shot-start pressure were repeated with the correct initial gas temperature, 300°K. The reasons for not repeating the other parts of the study are that: (a) piston performance is affected only by the propellant and the parametric constants of the piston, and (b) effects of the initial gas temperature on the value of model resistive pressure are expected to be minimal.

Results of this second effort to determine the value of model shot-start pressure are shown in Figure 11. Also indicated in this figure are the model velocity data obtained during the proof testing of the 81/26-mm light-gas gun. This graph indicates that the value of model shot-start pressure which best simulates the gun performance is 2800 psi.

In summary, we can list the values of the parametric constants used during the computed performance analysis of the gun:

Piston shot-start pressure	4000 psi
Piston resistive pressure	500 psi
Model shot-start pressure	2800 psi
Model resistive pressure	0 psi

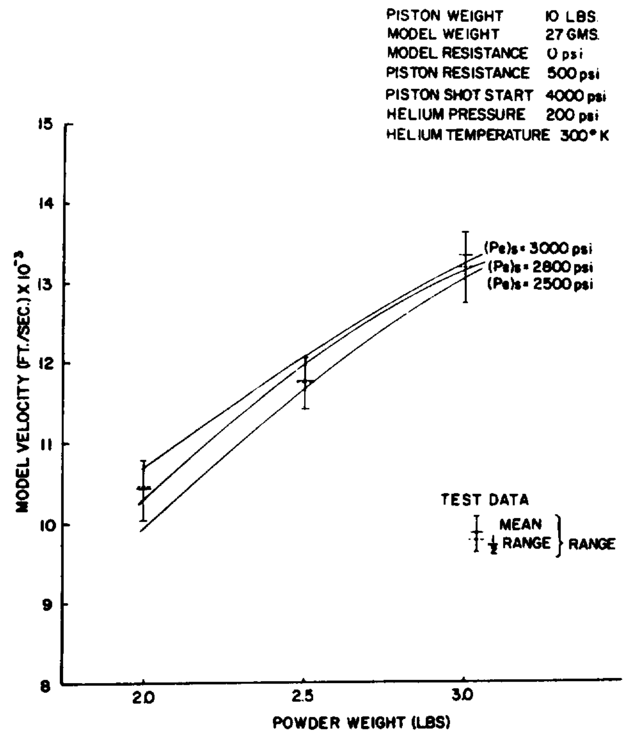

Figure 11. Model velocity vs powder weight, with model shot-start as parameter

COMPUTED PERFORMANCE OF 81/26-MM LIGHT-GAS GUN

After the parametric constants are determined, the computer program can be used to predict the performance of the gun with any loading condition. In this section we will (a) determine the maximum muzzle velocity, (b) display launch cycle characteristics under one loading condition, and (c) analyze the effect of doubling the powder weight on the model velocity and acceleration as functions of elapsed time.

In order to obtain a realistic value of the maximum model velocity, a strength limitation must be imposed on the gun. For this study, the strength limit was set so that the maximum permissible light-gas pressure during any part of the launch cycle must be less than 250,000 psi. This limit was reached with a powder weight slightly over 5.25 pounds for the loading conditions under consideration. The resulting muzzle velocity for a 29-gram launch weight was 21,700 feet per second.

Computed breech pressure and piston velocity dependence on the powder weight are shown in Figures 12 and 13, respectively. In Figure 12, the breech pressures measured during the proof tests are also shown for comparison. Since no test data were available for powder weights larger than 3.0 pounds, it is not possible to estimate the quality of simulation obtained in that regime.

Figure 13 shows that for the loading conditions under consideration the maximum calculated piston velocity is still below the initial speed of sound of the light gas (helium). In spite of both this and the low value of piston acceleration, there exists a system of strong shock waves in the launch tube; this will be shown later.

The variation of model velocity as a function of powder weight is shown in Figure 14. This curve indicates that the maximum attainable velocity, for the existing gun design and loading conditions considered, is already being approached.

Figures 15 and 16 show various aspects of gun performance during a launching cycle. These figures were obtained for a powder weight of 2.5 pounds. Variations of the piston velocity, breech pressure, and pressure of the pump-tube gas just ahead of the piston as functions of piston travel are shown in Figure 15. Figure 16 depicts the computed model velocity and base pressure as the model travels down the launch tube. Sharp peaks in the curve for the base pressure are indications of the existance of a system of shock waves that are traveling along the launch tube. This phenomenon is more evident in the printed output. Another interesting observation is that for the last 100 inches the model travels, the base pressure oscillates between 11,000 and 12,000 psi as compared to 9800 psi that would be required for the constant acceleration launching cycle.

Figures 17 and 18 compare the launcher operation at two different powder weights. Figure 17 shows model velocity as a function of time elapsed from the start of the model motion for powder weights of 2.5 and 5.0 pounds. One obvious difference between these two curves is the fact that the total launching cycle is about 30 percent shorter for the

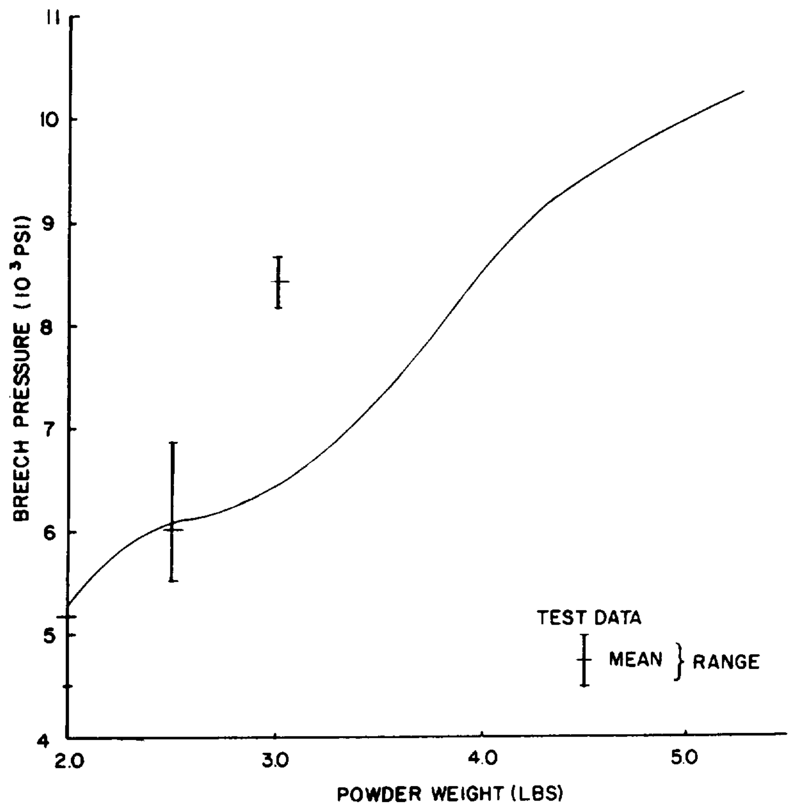

Figure 12. Breech pressure vs powder weight for 81/26-mm gun

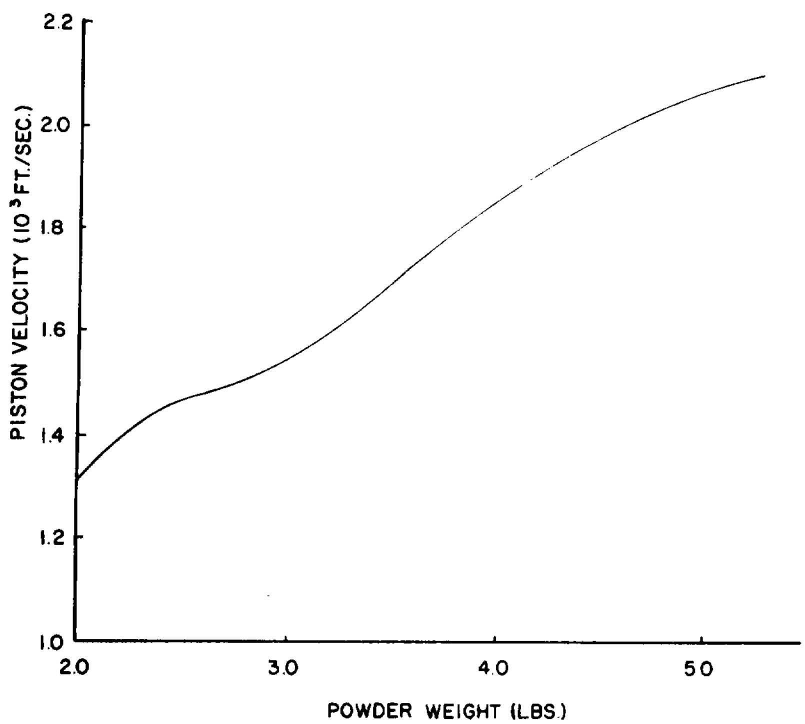

Figure 13. Computed piston velocity vs powder weight for 81/26-mm gun

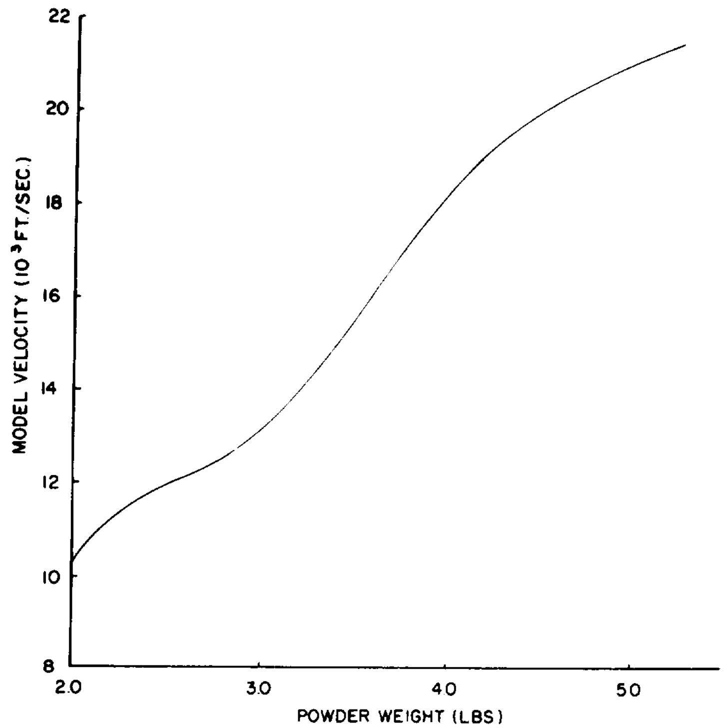

Figure 14. Computed model velocity vs powder weight for 81/26-mm gun

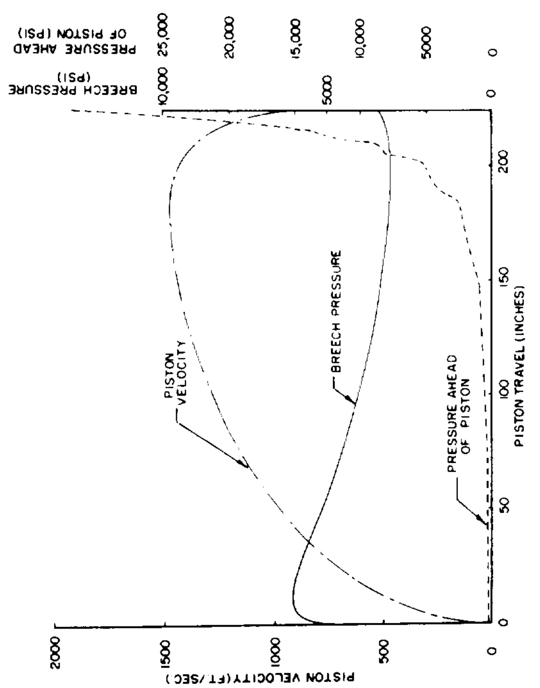

Figure 15. Breech pressure, piston velocity and pressure ahead of piston as functions of piston travel

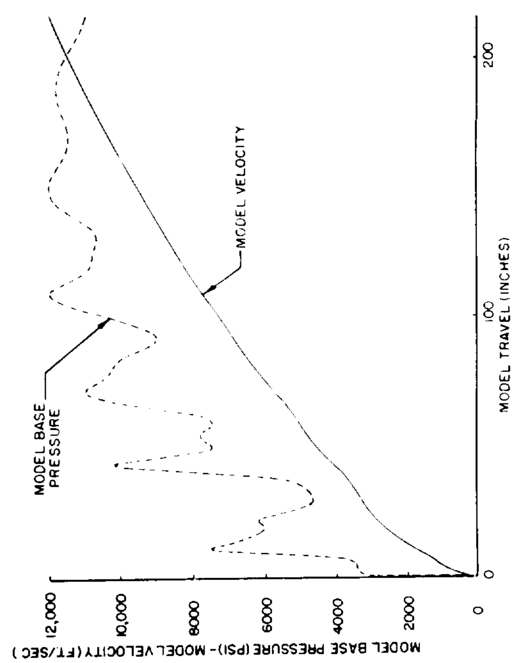

Figure 16. Model base pressure and velocity as functions of model travel

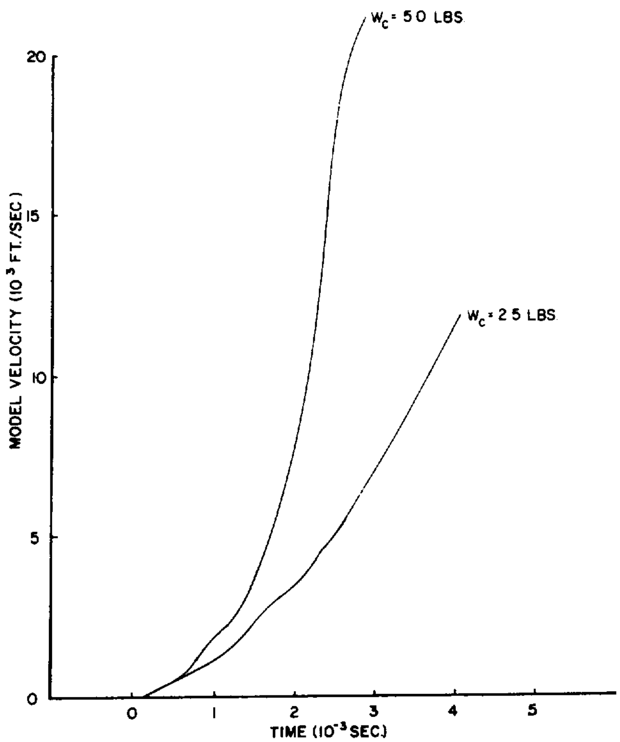

Figure 17. Model velocity vs time for 81/26-mm gun

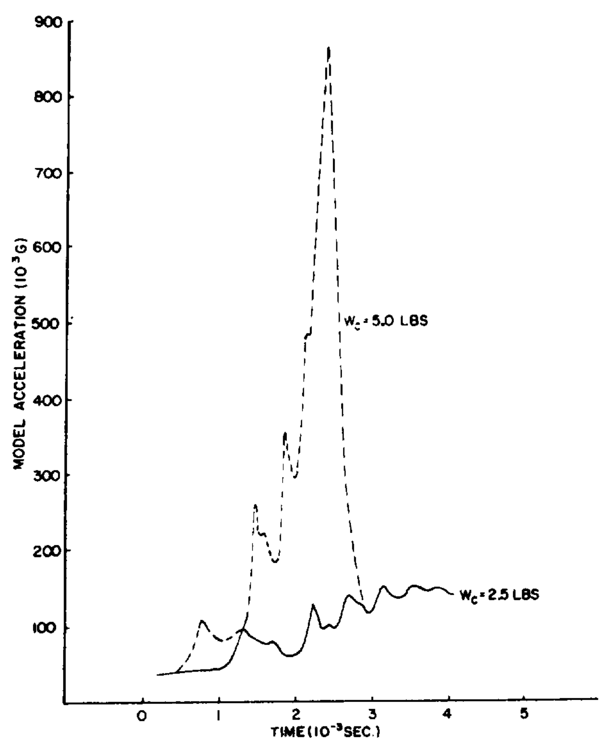

Figure 18. Computed model acceleration vs time for 81/26-mm gun

5.0-pound powder curve. Another important difference is that the 2-1/2-pound powder-weight curve is approaching a constant acceleration cycle during the last millisecond of the launching, as shown by the almost linear increase of the model velocity with time, while the velocity history of the 5-pound powder-weight curve does not bear any relation to a constant acceleration launching cycle. Finally, from the velocity data for the 5-pound powder-weight calculations, we can see that the model base pressure is falling rapidly, as it would for a conventional gun. The reason for this behavior is apparent from the printout data for this computation, i.e., the model velocity is about three times the instantaneous local speed of sound at the time of exit.

Acceleration histories for these two calculations are compared in Figure 18. Facts which were implied by the velocity-time relationships are more clearly indicated by these curves. For the low powder-weight launching cycle, the model acceleration oscillates about an average value of 145,000-g (compared with a value of 124,000-g required by the constant acceleration cycle) during the last millisecond of the launching. The acceleration history of the high powder-weight launching is characterized by an "Alpine" peak reaching 870,000-g, compared with a constant acceleration of 391,000-g needed for the same model velocity.

Based on these computer analyses, some of which are discussed above, it is concluded that the BRL 81/26-mm light-gas gun is capable of launching 29-gram saboted models at velocities just under 22,000 feet per second. However, this would require sophisticated model and sabot designs which will remain intact under acceleration loads of approximately 1,000,000-g.

ACKNOWLEDGEMENTS

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13. ABSTRACT

A computer program and its use to simulate the performance of a light-gas gun is described. This technique is applied to simulate proof tests of the 81/26-mm light-gas gun. The analysis is extended to determine performance characteristics and maximum muzzle velocity attainable with a 29-gram launch weight. Results of computer analyses indicate that a sabot/model combination of that weight could be launched at a velocity above 21,000 feet per second if it could be designed to withstand about 1,000,000-g acceleration loads.

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